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Scientific note

Arctic Ocean change and consequences to biodiversity: A perspective on linkage and scale

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Abstract: In the Arctic Ocean at least two climate-linked, contiguous domains are linked to ecosystems through both bottom-up (e.g. changes in light and nutrient regimes) and top-down (*e.g.* changes in fish and large predator populations) regulation. The first is the $\sim 7\times 10^6$ km^2 seasonal ice zone (SIZ) which affects light and nutrient regimes, and also provides a solid surface upon which large mammals travel, rest, reproduce and hunt. The second is the $\sim 10\times 10^3$ km long riverine coastal domain (RCD), driven by runoff, which affects light, nutrient and carbon regimes and provides a pathway for the dispersal and migration of marine biota. Sustained observation of marine mammal and bird behaviour may unlock 'top-down' information to an important ecological question raised by Malcolm Ramsay (pers. comm.), namely: What environmental conditions prompt certain animals to be in a certain place at a certain time, and how will they respond to changing climate conditions? Finally, it is noted that the Arctic is not an isolated sea, but rather is interconnected to the water masses and ecosystems of the Pacific and Atlantic.

1. Introduction

Conservation of biodiversity, particularly those components upon which humans depend for survival, is arguably the most pressing challenge facing environmental scientists in the new century (*cf.* Levin, 1999). This challenge must be addressed against a backdrop of rapidly changing environmental conditions and constraints, and nowhere is this backdrop changing more rapidly than in the Arctic.

Prior to the 1990s, the water mass structure of the Arctic Ocean was generally held to be in steady state. However growing evidence of change has been documented in both the Arctic Ocean water column (*cf.* Carmack *et al.*, 1995, 1997; McLaughlin *et al.*, 1996; Morison *et al.*, 1998; Steel and Boyd, 1998) and in its ice cover (Kwok and Rothrock, 1999). Such studies appear to parallel climate model predictions that climate warming will occur first and most intensely in high-latitude regions (Walsh and Crane, 1992). How, then, will biota respond?

The disproportionate influence of climate warming on Arctic physical and biological systems may also be linked to critical temperatures involving the melting of sea ice and snow. Physically this involves two main positive feedback mechanisms: the first is the so-called albedo feedback mechanism associated with the melting of snow and ice; the second is associated with the release of natural greenhouse gases (*e.g.* methane, CO_2) stored in the permafrost and hydrate layers at high latitudes. Biologically, the disproportionate influence of warming may alter the floating ice cover, and change the timing and strength of river freshet. It is the purpose of the following research note to review the basic structure of the Arctic Ocean; highlight recent observations of change; speculate on potential biological consequences; and, finally, discuss how changes in the physical environment may produce bottom-up and top-down consequences.

2. Ocean structure

The Arctic is a salt-stratified ocean. This allows the Arctic Ocean the stratification it requires to support an ice cover. The Arctic mixed-layer consists of the upper 50 or so meters wherein changes involving the annual melt-freeze cycle and river water disposition occur. Below this seasonally variable mixed-layer lies a complex of cold, salt-stratified layers known collectively as the Arctic halocline. This layer insulates the Arctic Ocean and keeps the upper cold waters cold and the underlying warm waters warm. Regionally, the various components of the Arctic halocline can be ascribed to (1) ice melt mixed with Atlantic-origin water, (2) Pacific-origin inflow waters (summer and winter), and (3) brine-enriched shelf drainage. Water mass boundaries separating waters of different source are found both in the vertical and the horizontal, and such boundaries are now known to shift from submarine ridge to ridge on inter-decadal time-scales. Such shifts are likely to alter downstream conditions in the North Atlantic as a result of the displacement of freshwater (McLaughlin, 2000). It is also important to view the Arctic mixed-layer and halocline as components of a much larger oceanographic feature, the northern hemisphere halocline, a domain bounded by sharp subarctic fronts in both the Pacific and Atlantic oceans. It is this latter feature that ultimately defines the presence or absence of both ice cover and deep convection at high latitudes.

Below the cold halocline lie components of the Atlantic layer, situated below the Arctic thermocline and above the effective sill depth of the Lomonosov Ridge (about 1600 m). Water within this layer enters from the North Atlantic via Fram Strait and the Barents Sea and moves counter-clockwise as narrow (about 100 km) cores following shelf-break and ridge topography. The deep waters of the Arctic Ocean lie below the effective sill depths of the Lomonosov and Alpha/Mendeleyev ridges and are among the most isolated in the world.

Arctic Ocean outflow occurs via both Fram Strait and the West Greenland Current (Woodgate *et al*., 1999) and through the Canadian Arctic Archipelago (Melling, 2000), and both outflows are complex. For example, transformations within the East Greenland Current are thought to play a role in the formation of Denmark Strait Overflow Water (Strass *et al*., 1993). Outflow through the Canadian Arctic Archipelago occurs across an extremely large and complex arctic shelf, studded with islands, and characterized by interconnected sub-basin, tidal and buoyancy-driven boundary currents.

3. Arctic environmental change

It is currently thought that there are two main ways that the Arctic Ocean might impact on global climate, and both relate to the high-latitude hydrological cycle (*cf.* Aagaard and

Carmack, 1989, 1994). The first is through its effect on the surface heat balance, *i.e.* the role of the ocean, sea ice and clouds in the local radiation balance and albedo. The second is through its effect on the global thermohaline circulation, *i.e.* the regulation of deep-water formation rates. But, climate change is a two-way street, and we must also ask the question: How will global climate variability impact back, regionally, upon the Arctic and its biodiversity?

3.1. What are the signs of Arctic change?

This past decade has witnessed remarkable variability in the physical environment of the Arctic region, variability that may have consequences to all forms of life. Figure 1 depicts a number of key changes in a cartoon 'climate clock' where each passing hour records different physical changes.

- One o'clock: Perturbations in the amount of low salinity water exiting the Arctic have affected the upper waters of the entire North Atlantic Ocean (and perhaps the thermohaline circulation) on decadal time scales (Dickson *et al.*, 1988; Belkin *et al.*, 1998).
- Two o'clock: Temperature of Atlantic origin water entering through Fram Strait and the Barents Sea has increased (Quadfasel *et al.*, 1991; Carmack *et al.*, 1995, 1997; Morison *et al.*, 1998; Grotefendt *et al.*, 1998).
- Three o'clock: Transport of surface waters toward exit points at Nares and Fram straits has increased (Newton and Sotirin, 1997).

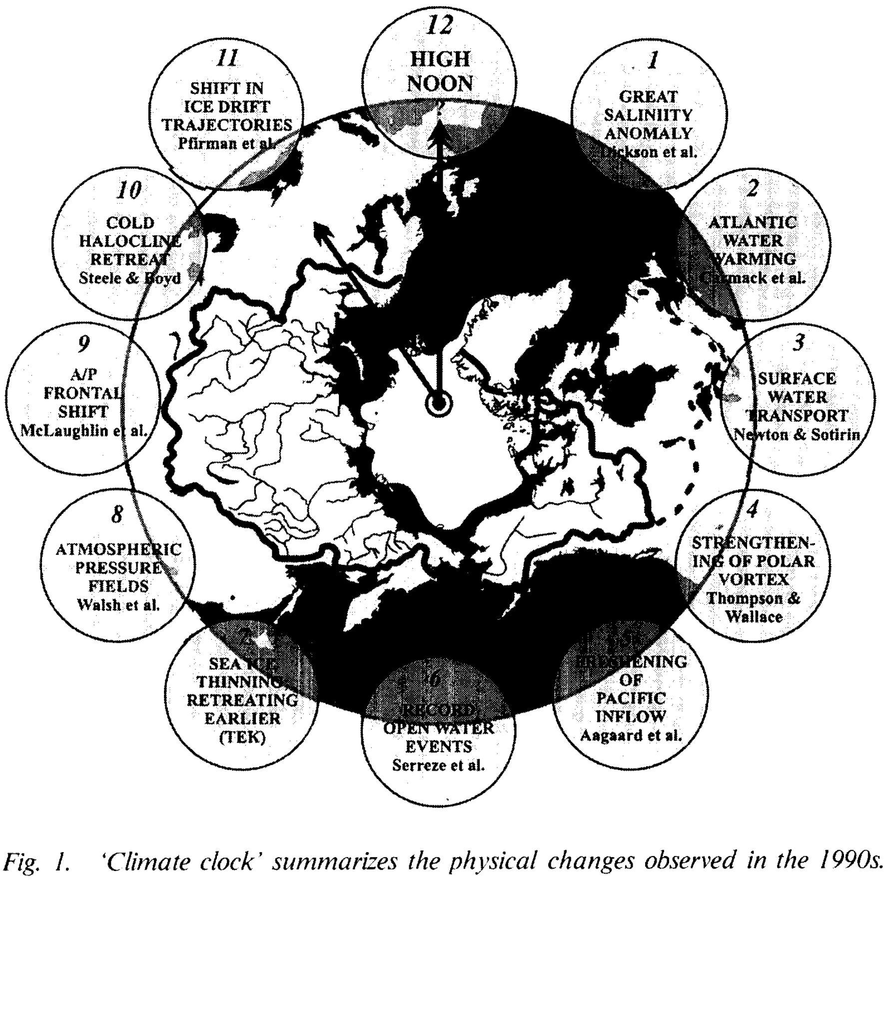

Fig. 1. 'Climate clock' summarizes the physical changes observed in the 1990s.

- Four o'clock: Polar vortex has strengthened and the Arctic Oscillation is now recognized as a fundamental mode of the global atmosphere (Thompson and Wallace, 1998).
- Five o'clock: Salinity of Pacific origin water entering through Bering Strait has decreased (Aagaard, pers. comm.)
- Six o'clock: Record areas of open water during summer (Serreze *et al.*, 1995).
- Seven o'clock: Sea ice has been noted to be decreasing in areal extent, thinning, more mobile, melting earlier and re-freezing later (Traditional Ecological Knowledge).
- Eight o'clock: Mean atmospheric pressure over the Arctic has decreased, reflective of an increased number of atmospheric cyclones entering the arctic system (Walsh *et al.*, 1996).
- Nine o'clock: A basin-wide water mass front separating Atlantic and Pacific water masses has abruptly shifted from one ridge system (the Lomonosov) to another (the Alpha-Mendeleyev) (McLaughlin *et al.*, 1996).
- Ten o'clock: Areal extent of the so-called cold halocline (which provides static stability to the water column) has retreated (Steele and Boyd, 1998).
- Eleven o'clock: Large-scale trajectories of sea-ice have changed (Pfirman *et al.*, 1997).
- Twelve o'clock: As in the western film "High Noon" this is a time when the protagonist (mankind) must take moral and decisive action—in this case with the environment—or forever live with the consequences.

3.2. What are the potential consequences to biota?

Variability in the physical environment is likely to be reflected in the realm of living nature, including changes in species abundance, community structure, seasonal distributions, geographic range, migration patterns and reproductive success. The ecological importance of biota living below, within and above sea ice has been discussed by Alexander and Chapman (1981), Burns *et al.* (1981), Bradstreet (1982), Grebmeier *et al.* (1988) and Welch *et al.* (1992). Stirling and Derocher (1993) and Tynan and DeMaster (1997) have discussed consequences of climate change to marine mammals. Drawing from these works, among others, we present Fig. 2 as a 'biological clock' that summarizes a number of conceptual scenarios, both bottom-up and top-down, that might follow from climate change.

- One o'clock: Warming will result in longer ice-free periods, particularly in the seasonal ice zone.
- Two o'clock: Increased open water will increase wind-mixing, upwelling, and wintertime brine rejection (convection), and thus increase the availability of nutrients to phytoplankton.
- Three o'clock: Increased open water will increase the availability of underwater light to phytoplankton, especially in the seasonal ice zone.
- Four o'clock: Increased rainfall predicted under global warming will increase the export of organic terrestrial material (POC, DOC) to coastal domains.
- Five o'clock: Decreased ice cover will decrease ice algae production with consequences to the marine food web.
- Six o'clock: Rising sea level, combined with increased temperatures and open water areas, will accelerate coastal erosion.
- Seven o'clock: Shifting water mass fronts and currents will affect fish migration and behaviour.
- Eight o'clock: Altered habitat conditions in both rivers and coastal seas may affect the

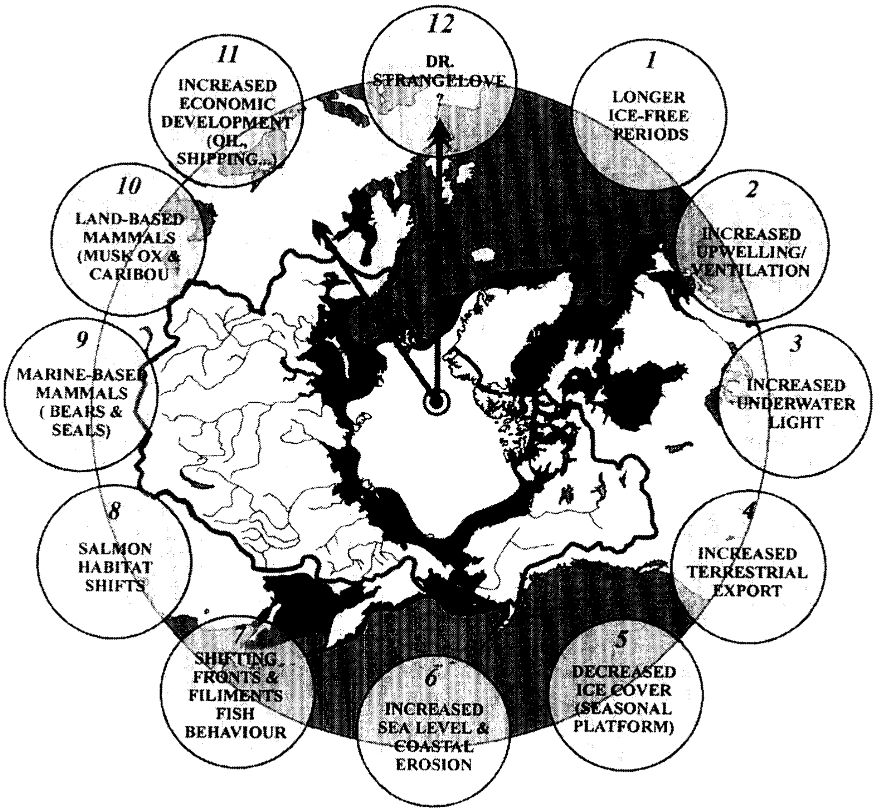

Fig. 2. 'Biological clock' summarizes a number of biological scenarios that might follow from climate change.

distribution of anadromous fish.

- Nine o'clock: Marine-based animals (*e.g.* seals, bears) that depend on an ice platform will be seriously impacted by loss of habitat.
- Ten o'clock: Land-based mammals (*e.g.* caribou) that depend on a reliable seasonal platform of ice for migration will be impacted.
- Eleven o'clock: A warmer climate will attract extractive, resource-based industries (*e.g.* oil, mining) with the result that human conditions and impacts will change.
- Twelve o'clock: As in the film "Dr. Strangelove" which refers to a doomsday device buried in the Arctic capable of extinguishing all life, the cumulative effects of climate change may trigger natural doomsday devices (*i.e.* runaway feedback mechanisms) that the Arctic may possess. For example, the release of billions of tonnes of methane (a greenhouse gas) held beneath the frozen Arctic surface could be triggered by global warming with catastrophic effects.

The above 'clock' maintains a separation in the responses of plankton, fish and mammals to environmental change, whereas in fact, they are coupled, a point discussed below.

4. Discussion

Wilson (1999) defined biodiversity as: "The variety of organisms considered at all levels, from genetic variants belonging to the same species through arrays of species to arrays of genera, families and still higher taxonomic levels; (it) includes the variety of ecosystems, which comprise both the communities of organisms within particular habitats and the physical conditions under which they live." Biodiversity thus refers to what is there. More recently the term biocomplexity has been applied and refers to how what is there senses and interacts with its environment. Biocomplexity views nature as a complex adaptive system, wherein the problem of pattern and scale is the central challenge (*cf.* Levin, 1992). To link biodiversity to climate simply requires that we accommodate all scales from that of the molecular to that of the climate (Fig. 3). This 'working through scales' is typically done in either ascending or descending order. The bottom-up approach views trophic interactions

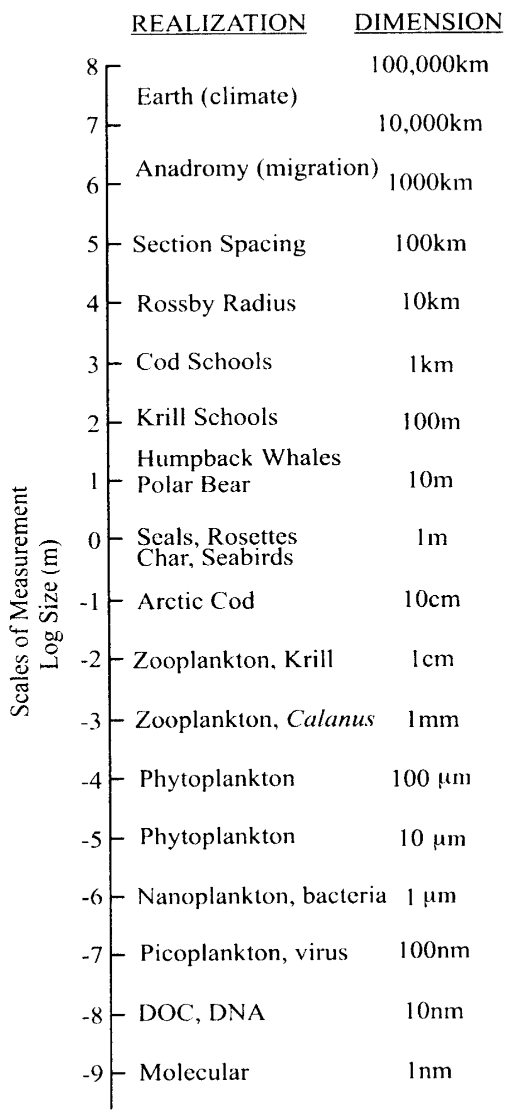

Fig. 3. Scales linking climate to biota.

as a chain beginning with small scales and working upward (*e.g.* turbulence delivers nutrients which fuel primary production, and so on). The top-down approach begins at some larger scale and works downward to understand, for example, the role of predators in shaping trophic structure. It is commonly assumed that climate change effects bottom-up changes (*e.g.* nutrients, underwater light conditions), and that anthropogenic impacts (*e.g.* fishing, whaling) work in a top-down mode. Seldom is the full set of scales linking climate to biodiversity within a contiguous ecological domain accommodated. In the Arctic, two climate-linked, contiguous domains can be identified where global warming may impact ecosystems from the bottom-up and the top-down.

4.1. Seasonal ice zone (SIZ)

Each year over 7 million square kilometres of sea-ice freezes and melts in the Arctic, an area about the size of the Australian continent. The top of this solid cover serves as floating platform for many large mammals, such as polar bears and seals and the underside provides a rich habitat for plankton and fish. Global warming, by shrinking and thinning the seasonal sea-ice, affects the geographical range and survival of many Arctic species. Shorter duration of ice cover by earlier break-up and later freeze-up may also impact on the timing of annual cycles critical to the Arctic environment.

Viewing recent changes from the bottom-up, a number of consequences may be anticipated. Longer ice-free periods will significantly increase underwater light availability. (At present, ice lingers through May and June, months of high insolation.) A delayed freeze-up will also expose more open water to forcing by autumn storms. Retreat of the SIZ into the central Arctic basins will impact nutrient availability on shelves during summer and autumn through increased mixing and upwelling. There may be an increase in productivity should the SIZ routinely retreat past the shelf break and allow coastal upwelling of nutrient-rich water from the basin interior.

Taking a top-down view we can ask: Could climate change in the Arctic Ocean also pose a threat of extinction to seals that require snow and ice to birth their young? Or polar bears that hunt only from sea ice? Or non-marine animals such as some populations of caribou that depend on a solid and reliable ice cover for their seasonal migrations to calving grounds? Removal and/or replacement of such predators from the adaptive ecosystem will clearly have top-down consequences.

4.2. Riverine coastal domain (RCD)

A key process in the transport of fresh water through the Arctic is via the formation of gravity-driven, buoyancy-boundary currents (Muchow and Carmack, 1997). Such flows form when fresh, low-density water is discharged into the higher-density ocean, and are deflected to the right by the Coriolis force. In the Northern Hemisphere, buoyancy-boundary currents travel in a clockwise sense, with landmasses always to the right in the direction of flow. The dimension of buoyancy-boundary currents scales with the Rossby radius $R_R=(g^*h)^{1/2}/f$, where g^* is the reduced gravity, h is depth, and f the Coriolis term; in the Arctic $R_R \sim 10$ km. This parameter scales the width of currents driven by coastal runoff.

The multiple sources of freshwater discharge from northern North America, combined with ice and snow melt, may enable the formation of a quasi-contiguous domain, here

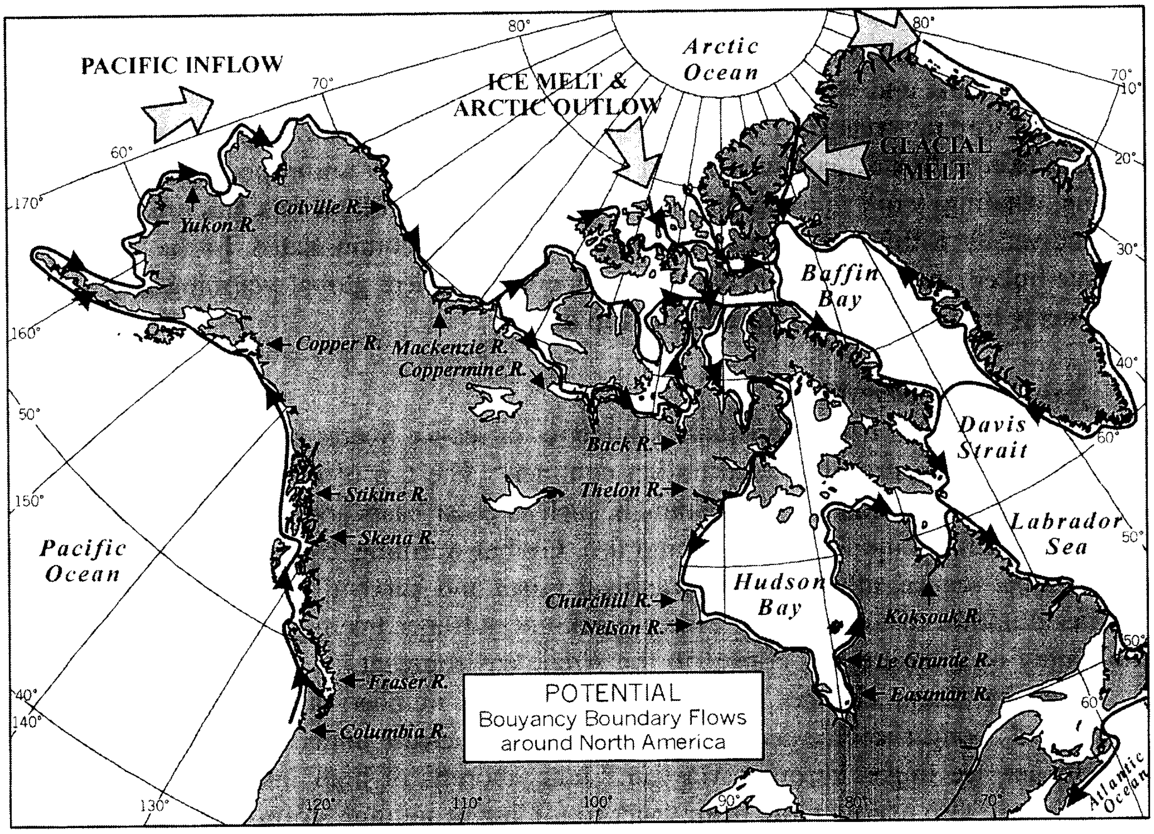

Fig. 4. Schematic representation of potential buoyancy-driven boundary flow around northern North America.

called the Riverine Coastal Domain (RCD), which extends around the northern part of the continent. This concept is shown schematically in Fig. 4. The RCD is not stationary or continuous; it is highly idealized in that it ignores wind and tidal forcing. However, it is (a) contiguous—more or less continuous around the entire continent; and (b) terrigenous—having a strong influence of land/ocean interaction. This contiguous and terrigenous ribbon around North America, if demonstrated, could provide an important migration and dispersal corridor for biota, and is of sufficient size and extent to be strongly linked to the climate system.

Taking a bottom-up view, some consequences of climate variability on the RCD are evident. Climate models predict increased precipitation in high-latitudes under greenhouse gas warming. This may result in altered runoff and export of terrestrial carbon (POC, DOC) to coastal ecosystems. Increased runoff may also alter erosion, suspended load transport, and thus the turbidity and light climate of coastal waters.

Top-down impacts may be even more important, as it is clear that such a pathway would play a major role in dispersal. Many anadromous fish species (salmon, cisco, char) use the RCD as a migration (and perhaps navigation) pathway. Do recent observations of increased numbers of Pacific salmon in Arctic rivers signal new colonizations associated with global warming? Finally, the ecological consequences of macro-plankton grazers, carried by density currents over great distances to new pastures, because of a changing physical environment, are beyond speculation.

5. Concluding remarks

Although this note has focused on the impacts to arctic biota of changing climate, the effects of human activity upon this fragile ecosystem must also be weighed. In the Canadian Arctic we should inquire, for example, has the abundance and diversity of life in Arctic waters changed since the time Henry Larsen sailed aboard the *St. Roch*? Since the time John Franklin's party sailed aboard the *Erebus* and *Terror*? Since Parry, Hudson and Frobisher entered the Arctic in search of a trade route? Has removal of top predators by whaling, hunting and fishing irreversibly altered the trophic dynamics of Arctic waters, thereby changing productivity and increasing vulnerability to climate change? Likely, the answer to each question is yes. But, can the magnitude of such change be measured or understood? Likely, it cannot. Nevertheless, an important beginning can be made by studying oral history, examining archaeological records and reviewing scientific data that already exists.

Around the world, Aboriginal Peoples have long held that all nature is interconnected. Certainly, this is true of the oceans surrounding North America. Low salinity waters from the Pacific Ocean flow northward through Bering Strait carrying nutrient-rich waters into the Arctic Ocean. This water floods the upper layers of the Beaufort Sea, and much of it eventually exits eastward from the Arctic Ocean through the Canadian Arctic Archipelago and into the North Atlantic via the Labrador Sea. In this way, Pacific waters transiting the Arctic, may eventually condition the marine habitat of Atlantic fishes. This simple example shows that we cannot truly understand changes that occur in one ocean without viewing the entire system.

Acknowledgments

This brief contribution is dedicated to the vision, inspiration and scientific leadership of Malcolm Ramsay, who woke us both to the beauty and importance of the Arctic's living nature.

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